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Article

Contribution of Onshore Power Supply (OPS) and Batteries in Reducing Emissions from Ro-Ro Ships in Ports

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Abstract: Increasingly restrictive environmental regulations for the maritime sector have led shipping companies to look for technological alternatives to reduce emissions. This article introduces a methodology to analyse emission reductions of ships in port by incorporating batteries into the ships or using an onshore power supply system. These have not yet been considered together for comparison or with a focus on ship operation. The aim is to avoid the use of auxiliary engines in ports. First, the cost calculation method to be used is specified; then, the engine's behaviour and the established basic navigation criteria are analysed; and finally, different alternatives are considered. A methodology is afterwards defined for selecting alternatives, comparing their costs with those of using auxiliary engines in port. As an example, it is applied to a Ro-Ro route between the ports of Montoir (France) and Vigo (Spain). The results indicate that incorporating batteries into the ship produces greater savings in annual costs than onshore power supply. The cost savings from onshore power supply depend on the range of prices in each port. However, the greatest emission savings are obtained by using the onshore power supply. This methodology can be extrapolated to other routes and vessels by incorporating real operating data.

Keywords: ship emissions; Ro-Ro ships; battery; onshore power supply (OPS); specific fuel consumption curve; shaft generator; auxiliary engines; main engines

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1. Introduction

In this Introduction, three aspects will be highlighted: the motivation and regulations from which the article arose, a technological review of the latest advancements in ship electrification and the use of renewable energy, and the objective of this article.

1.1. Motivation and Regulations

In 2018, the world greenhouse gas (GHG) emissions from all shipping (international, domestic, and fishing) reached 1076 million tonnes, about 2.9% of global anthropogenic emissions. Moreover, carbon dioxide (CO_2) alone accounted for 98% of GHGs [1].

In the same year, ships stopping in ports within the European Union (EU) or European Economic Area emitted around 140 million tonnes of CO_2 [2]. Furthermore, around 40% of the emissions were produced during voyages between ports of EU Member States and while ships were at berth. For these reasons, the norms on controlling ship emissions are increasingly restrictive.

Internationally, they are regulated by Annex VI of the MARPOL Convention "Prevention of Air Pollution from Ships" that was added to the 1997 Protocol of the International Maritime Organization (IMO) [3]. This establishes a progressive reduction in SOx, NOx, and PM emissions and the introduction of emission control areas (ECAs). To improve the energy efficiency of ships and reduce their emissions, amendments to this Annex VI were carried out in 2021. As of 1 January 2023, it is mandatory for all ships to calculate their attained Energy Efficiency Existing Ship Index (EEXI) to complete the following:

- Measure their energy efficiency;
- Initiate the collection of data for the reporting of their annual operational carbon intensity indicator (CII) and CII rating [4].

Regarding the European Union, the European Green Deal [5] was approved in 2019 and developed by the European Climate Law [6] and the package of proposals "Fit for 55" [7] in 2021. These documents have set ambitious targets for reducing the net emissions by at least 55% by 2030 compared to 1990 and becoming climate neutral by 2050. To this end, the European Union has achieved the following:

- Included a maritime sector in the greenhouse gas emission trading system (EU ETS), Directive (UE) 2023/959 [8];
- Imposed a limit on the greenhouse gas (GHG) intensity of energy used on board by a ship arriving at, staying within, or departing from ports under the jurisdiction of a Member State with Regulation (EU) 2023/1805 [9];
- Established an obligation to use an onshore power supply (OPS) or zero-emission technology in ports under the jurisdiction of a Member State through Regulation (EU) 2023/1805 [9] and Regulation (EU) 2023/1804 [10].

Current practice for vessels staying in ports is to use their auxiliary engines to provide the power needed for loading, unloading, and berthing.

Given the need to comply with regulations, this article aims to analyse the measures that allow auxiliary engines to be stopped in Ro-Ro vessels in port to reduce their CO_2 emissions.

1.2. Technology Review

In addition to using an onshore power supply (OPS) and alternative technologies or fuels such as renewable energies, fuel cells, or liquefied natural gas (LNG), another growing option is to incorporate onboard batteries.

Rapid battery evolution in recent years in the automotive industry has greatly favoured their current application in the maritime sector. The most used batteries are lithium-ion, a type characterised by its high storage capacity and energy supply, which can best suit the conditions of space and weight in a vessel [11,12].

Their cost was initially a problem, but the influence of the automotive industry means that battery production costs in 2030 are expected to be half those in 2018, reaching a price of 100 USD/kWh by 2030 for automotive batteries [11], or to be 40% lower in 2030 compared to 2020 [12].

The fitting costs in 2020 for a vessel's lithium battery storage system were between EUR 600 and EUR 1000 per kWh, and this is forecast to drop by 30% by 2030 and by 50% by 2040 [11].

Applying batteries as a propulsion force is limited to vessels that make short journeys and charge their batteries in port: ferries, dynamic positioning ships and platforms, tugs, dredging ships, short-range ships, wind farm support vessels, etc. The first ship with hybrid/battery propulsion was the Viking Lady offshore supply vessel in 2011, under the FellowSHIP research program. The conversion of the propulsion system included the installation of a 442 kWh lithium-ion battery and a 320 kW fuel cell. According to the results, the following reductions were achieved: fuel consumption by 10–15%, NO_x emissions by 25%, GHG emissions by 30%, and maintenance costs. In addition, the machinery's performance, utilisation, and flexibility were improved. Following the good results, the shipping company converted three more vessels (Viking Queen, Viking Energy, and Viking Princess). In 2022, Yara Birkeland was the first fully electric and autonomous container ship put into commercial operation. For propulsion and manoeuvring, the vessel is equipped with an electrical system consisting of a battery pack of 6.7 MWh, two electrical azipull pods (2 × 900 kW), and two tunnel thrusters (2 × 700 kW). A reduction in CO_2 emissions per year of approximately 700 tons is expected [12].

The most recent example is the 100% electric catamarans designed by Gondan Shipyards for the Portuguese public company Transtejo in 2023 [13]. They provide regular public transport on the Tagus River in the Lisbon area. Since they are powered entirely by electricity (batteries), their operation is silent, and they do not emit CO_2 into the atmosphere.

Ocean-going vessels have different energy needs and make longer voyages, and so they tend to use batteries in combination with other renewable energy sources or alternative fuels [11,12,14]. Pan et al. [14] review the progress made in the integration of renewable energy sources (solar, wind, and fuel cells) in ships. They analyse how these sources are integrated into the ship's conventional system, show examples of existing ships with these technologies, and outline the challenges to be overcome from a technical and economic point of view. All three sources are promising alternatives. Both solar and wind power are limited by space on the ship's deck. Perhaps the most developed for immediate application is solar photovoltaic power (improving the efficiency of the panels is recommended), as wind power requires further feasibility studies, and fuel cells are still at a preliminary stage.

In addition to the study of the installation of these hybrid systems, recent articles also focus on their simulation and optimisation. Laryea et al. [15] performed the calculation, simulation, and optimisation of a hybrid renewable energy system (HRES) to ensure continuous power supply to auxiliary loads and critical systems on both conventional and fully autonomous tugs. The HRES includes diesel generators, photovoltaic panels, vertical axis wind turbines, and battery banks. The analysis shows that the fully autonomous tug performs better in terms of costs, CO_2 emissions, and renewable fractions compared to a conventional tug. In [16], a simulator based on dynamic programming was developed for the evaluation of the performance of hybrid electric propulsion vessels with batteries. As a result, a 9% improvement in fuel efficiency was obtained. Furthermore, in [17], uncertainties associated with renewable energy, waves, and ship motions are addressed, as they significantly impair and complicate ship operation and navigation. The aim is to jointly optimise energy management and voyage scheduling. Therefore, this paper develops a new, comprehensive one day-ahead probabilistic scheduling algorithm for a solar PV system, which combines the orthogonal Taguchi method with adaptive multi-objective particle swarm optimisation. The simulation results improve both ship punctuality and onboard PV energy production with lower costs and emissions.

In addition, in the specific case of hybrid battery systems, the subject of this article, the following have also been analysed:

- Hybrid systems with batteries for propulsion, assessing the efficiencies of power system architectures for a cruise liner with direct or alternative current [18]: for the studied load profile and the used control algorithm, the hybridisation of batteries on board a cruise ship increased the energy efficiency regardless of the power system architecture employed.
- Hybrid propulsion systems with batteries and shaft generators that can act as an engine (propulsion support) or a generator (electricity supply) for a ferry [19] or a fishing vessel [20]: In the first case, the simulation results show that hybrid electric systems achieve lower fuel costs compared to diesel mechanical and fully electric systems. In the fishing vessel case, the results of the proposed advanced energy management algorithm optimise energy utilisation, reduce fuel consumption, and improve the operational performance of the vessel.
- Batteries for the power system with generators to reduce emissions in port, with the batteries either being charged by the generators or by the onshore power supply in the case of a container ship [21]: From the analysis carried out, a reduction in CO_2 emissions is obtained between 8.6% (condition of higher energy demand) and 20.7% (condition of lower energy demand).
- Hybrid battery systems together with diesel generators, under different shared charge control strategies for various vessels (cruise liner, ferry, bulk, and container ships) and those which allow a generator to be substituted by batteries [22]: According to the results, the fuel savings strongly depend on the control strategies implemented and the type of ship. For example, the highest fuel saving potential through hybridisation is produced by the cruise ship, while the lowest is produced by the container ship.

Regarding Ro-Ro vessels, Table 1 shows examples incorporating hybrid systems with photovoltaic energy and batteries [23–25].

Table 1. Examples of hybrid Ro-Ro vessels.

Ship	Year	Photovoltaic	Capacity Battery (kWh)	Use	Charge Battery
COSCO Tengfei [25]	2011	143 kW	652.8	Lighting	Navigation
EMERALD ACE [23]	2012	160 kW	2200	Hotelling	Navigation
ECO VALENCIA [24]	2020	600 m^2	5000	Hotelling	Navigation with shaft generators

At the same time, projects such as OMB6 (Optimizing marine battery operations using 6 years' operational data from two commercially operating vessels) [26] and NEMOSHIP (NEw MOdular Electrical Architecture and Digital Platform to Optimise Large Battery Systems on SHIPs) [27] analyse the experiences gained from battery storage system installations in vessels in recent years. Their aim is to help in decision making when analysing the viability of future projects.

Finally, OPS can also be an interesting alternative. EU Regulation 2023/1805 [9] defines onshore power supply (OPS) as "the system to supply electricity to ships at berth, at low or high voltage, alternate or direct current, including ship-side and port-side installations, when feeding directly the ship main distribution switchboard for powering hotel and service workloads or charging secondary batteries". OPS has been in use for years and has been implemented at a low voltage since 1980 and at a high voltage since 2000 [28]. The Gothenburg Port was the first in which this high-voltage system was installed in 2000, in two docks of the Ro-Ro terminal [29,30]. From this moment, multiple studies have been carried out, for example, in Copenhagen Port [31], OPS Master Plan for Spanish Ports [32], Ningbo Zhoushan Port [33], technological review [34], ferry routes between the Negmar Eskihisar and Negmar Tavşanlı terminals [35], and technical, energy, and environmental aspects [36–38]. In addition, the Port of Vigo plans to launch OPS in 2025 for Ro-Ro ships [39].

1.3. Definition of the Objective

Consequently, considering the references analysed, the aim of this article will be to define a methodology for selecting the best alternative for in-port emission reduction for application in each case from the following:

- The use of onboard batteries in vessels, which are charged during navigation and supply the electricity needed when berthed;
- Onshore power supply (OPS), focused from the point of view of the ship and its operation.

These alternatives will be applied on a scheduled maritime route between the European ports of Montoir (France) and Vigo (Spain) undertaken by a Ro-Ro-type vessel—in this case, the Suar Vigo—which regularly carries out this route (Table A1). Their aim is to avoid the use of auxiliary engines in port and reduce emissions.

Regarding the features of the articles mentioned, the novelties of this one are as follows:

- It applies to the specific case of a Ro-Ro vessel because it has not been considered until now, and its traffic is important in the Port of Vigo. In fact, this port is among the main Spanish ports in the traffic of new vehicles and the first for Ro-Ro operation in the coastal strip of the entire Atlantic slope of the peninsula [40].
- It envisages that battery charging is undertaken by auxiliary engines and shaft generators during navigation. References [19,20] consider shaft generators, whereas [21,22] employ auxiliary engines. None studied them jointly.
- In addition to calculating fuel consumption and emissions, as in [21,22], the corresponding costs are also obtained.

- It not only evaluates the incorporation of batteries in the vessel but also the use of the OPS system. As described, both options are growing and booming for incorporation into the ship. In addition, the Port of Vigo plans to launch OPS in 2025 for Ro-Ro ships. The consulted articles analyse one alternative or another but not jointly and from the point of view of the vessel and its operation.

2. Methodology

Figure 1 defines the alternatives for analysis to achieve lower in-port emissions.

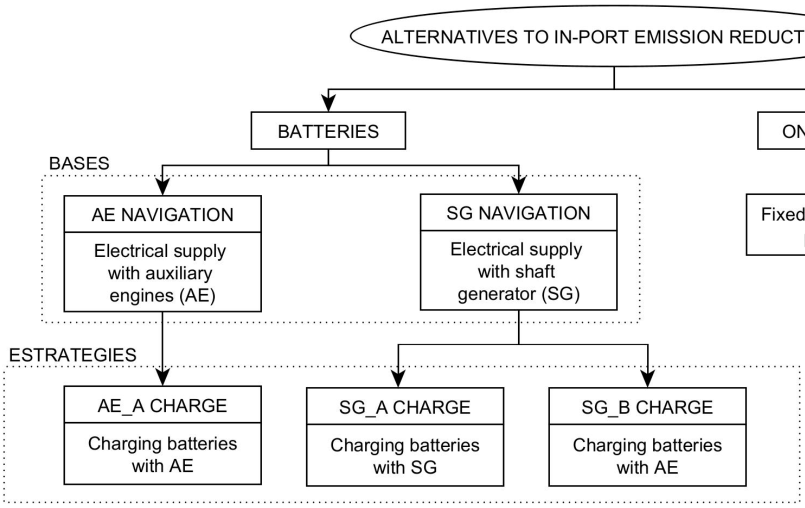

Figure 1. Definition of alternatives to emission reduction in port.

Section 2.1 of this work specifies the calculation method for the vessel's fuel consumption and emissions and the corresponding cost calculations used in this analysis.

Then, the vessel's engine performance is studied for each phase of the trip (navigation, manoeuvring, and hotelling), and the Base Navigation scenarios are established depending on the use of shaft generators (SG) or auxiliary engines (AE) to supply the ship's electricity demand (Section 2.2)

Subsequently, there is an assessment of the criteria to be applied when assessing the emission reduction alternatives through the incorporation of the following:

- batteries in the vessel (Section 2.3);
- onshore power supply, OPS (Section 2.4).

The fuel consumption calculation is performed from the specific consumption curve for the motors (main and auxiliary) according to the load factor (Section 2.2.1) and for each phase of the journey (Section 2.2.2).

At the same time, the electricity costs for OPS are calculated in a similar way as those for fuel, but they are based on the vessel's electricity demand.

Once the ways to calculate the consumption and costs for each of the alternatives are established for each Base Scenario and the use of auxiliary engines in port, the methodology will be defined for selecting the corresponding alternative to employ.

2.1. Fuel Consumption and Emissions Calculation Method and Their Respective Costs

When it comes to proposing any alternative for reducing emissions, it is important to calculate the fuel consumption and emissions for comparison between the initial situation and the proposed alternatives. In this way, it is possible to assess the possible savings.

If the power of the vessel's engines is known, then the fuel consumption (FC) in the different phases of the trip (navigation, manoeuvring, and hotelling) can be found by using Equation (1) [41–43].

As for emissions (E), a calculation method based on fuel consumption is used by means of Equation (2) [44–46]

$$FC_{j,f,p} = T_p \cdot \sum_m \left[\frac{SFC_{j,f,m} \cdot LF_m \cdot P_m}{10^6} \right]. \tag{1}$$

$$E_{i,j,f,p} = FC_{j,f,p} \cdot EF_{i,j,f,p} \tag{2}$$

where the following are true:

- FC: fuel consumption (t);
- SFC: specific fuel consumption (g/kWh);
- LF: load factor of MCR (Maximum Continuous Rating) of engines;
- P: engine nominal power (kW);
- T: time (h);
- m: engine category (main and auxiliary);
- j: engine type (slow-, medium-, and high-speed diesel, gas turbine, and steam turbine);
- f: fuel type (bunker fuel oil, marine diesel oil/marine gas oil, and gasoline);
- p: the phase of the trip (navigation, hotelling, and manoeuvring);
- i: pollutant;
- EF: emission factor (kg pollution/t fuel).

The emission factor based on fuel consumption has a value of 3179 kg CO_2/t fuel. It is a unique factor regardless of the type of engine or journey phase [45].

In accordance with Directive (EU) 2023/959 [8], the greenhouse gas emission trading system (EU ETS) must take into account the emissions from intra-community travel and stays in ports and 50% of the emissions from extra-community trips.

Additionally, fuel use in vessels is also regulated by norms in order to reduce SOx, NOx, and PM emissions:

- Internationally, they are regulated by Annex VI of the MARPOL Convention "Prevention of Air Pollution from Ships" that was added to the 1997 Protocol of the International Maritime Organization (IMO).
- At a European level, Directive (UE) 2016/802 [47] limits the sulphur content to 0.1% of the mass for marine fuels used by ships in port.

Therefore, the sulphur content of the fuels to be used in the vessel's engines will be as follows:

- General IMO: the vessel will always use fuel with 0.5% sulphur content for navigation, manoeuvring, and hotelling;
- Emissions control area (ECA) IMO or stay in port (EU) Directive 2016/802: the vessel can only use fuel with a 0.1% sulphur content.

Finally, the fuel or emissions cost will be calculated from the fuel consumption or emissions obtained using Equations (1) and (2) and their corresponding prices. The prices considered in this article are the following:

- MGO—0.1%: 944 USD/t [48];
- VLSFO—0.5%: 671 USD/t [48];
- Emission rights price of CO_2 (EU ETS): 79.7 EUR/t [49,50].

2.2. *Vessel Engine Performance Depending on Journey Phase*

This section analyses the performance of the vessel's engines in the different phases of a trip: navigation, manoeuvring, and hotelling.

The vessel Suar Vigo has the following [51]:

- Two main engines (ME) type MAN-B&W 9L 40/45 of 6480 kW, each one to 550 rpm;
- Two auxiliary engines (AE) of 620 kW, each one to 1500 rpm.

In addition, each main engine has one STAMFORD shaft generator of 810 kVA attached. According to the alternator manufacturer, its electrical power is 648 kW, input power is 679 kW, and efficiency is 95.5% [52].

The main engines are devoted to driving the ship, while the shaft generators or auxiliary engines are used to provide its electricity supply.

At the same time, according to the sources consulted [44–46,53], the load factor (*LF*) with respect to the phase of the trip is shown in Table 2.

Table 2. Load factor (*LF*) in different phases of trip depending on engine type: main engine (ME) and auxiliary engine (AE) [44–46,53].

Trip	LF_{ME} (%)	LF_{AE} (%)
Hotelling	20	40
Manoeuvring	20	50
Navigation	80	30

Furthermore, taking into account the speed of each type of engine—medium speed for main engine and high speed for auxiliary engine—the specific fuel consumption (SFC) is specified in Table 3 [45,53]. According to the sources consulted, there is no difference in the values between 0.1% and 0.5% marine gas oil (MGO) nor depending on the engine load factor.

Table 3. Specific fuel consumption (*SFC*) according to engine type (g/kWh) [45,53].

Trip	SFC_{ME} (g/kWh)	SFC_{AE} (g/kWh)
Hotelling	223	217
Manoeuvring		
Navigation	203	

2.2.1. Features of the Engines and Calculation of Specific Fuel Consumption Curves

When calculating the SFC curves for the Suar Vigo's engines, data are used from similar engines to those used in the vessel [54,55], and the values used are shown in Tables 4 and 5.

Table 4. Technical characteristics of the engines according to the manufacturer's specifications for each engine type: main engine (ME) and auxiliary engine (AE).

	ME	AE
Engine power (kW_m/cylinder)	530	120
Cylinder number	10	5
Engine power (kW_m)	5300	600
Engine speed (rpm)	750	1000
Generator power (kW_e)		561
Efficiency (%)		93.5
Power factor		0.8

Table 5. Specific fuel consumption (SFC) according to load factor (LF) for engine type: main engine (ME) and auxiliary engine (AE).

LF_{ME} (%)	SFC_{ME} (g/kWh)	LF_{AE} (%)	SFC_{AE} (g/kWh)
100	178.5	110	191.2
85	175.5	100	188.0
75	185.0	90	188.3
50	193.5	75	190.5
25	214.5	50	204.4
10	280.0	25	236.4

From the data specified in Table 5, the SFC curves for each of the engines, according to the load percentage, are obtained by calculating the second-degree polynomial regression equations. For the main engine, the regression fit gives an R^2 value of 0.9987, and for the auxiliary engine, 0.9993.

Figures 2 and 3 compare the SFC data provided by the manufacturer (Table 5) with the SFC curves resulting from the second-degree polynomial regression. The values of the SFC curve for the main engine are lower than those for the auxiliary engine curve, a fact that will be of great interest when considering the different battery charging strategies.

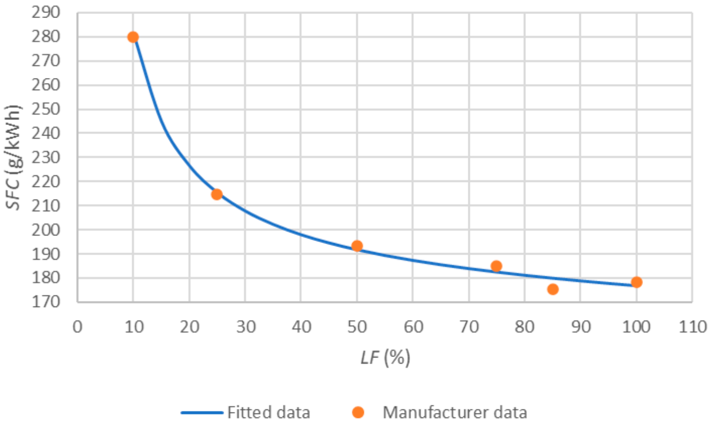

Figure 2. Comparison of the manufacturer's specific fuel consumption (*SFC*) data for the main engine and the fitted data in a specific fuel consumption (SFC) curve.

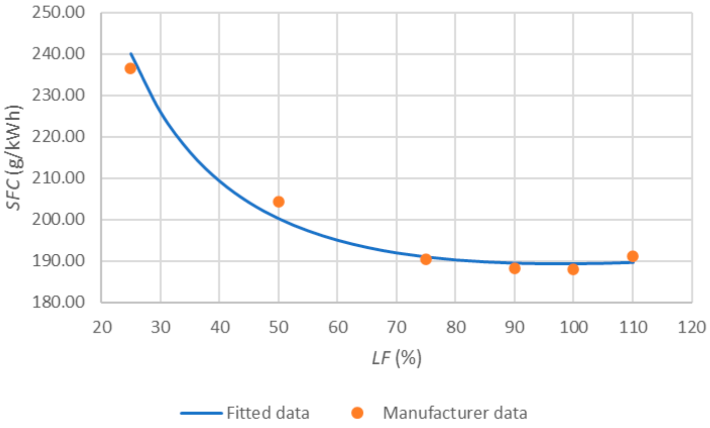

Figure 3. Comparison of manufacturer's auxiliary engine specific fuel consumption (*SFC*) data for the auxiliary engine with the fitted data in a specific fuel consumption (SFC) curve.

2.2.2. Hourly Fuel Consumption at Each Stage of the Journey

Taking into account the power of the ship's engines and their SFC curves, the hourly fuel consumption of the main and auxiliary engines is obtained according to the load factor percentage.

In order to validate the estimated number of engines in service and their *LF*, the consumption data obtained from the SFC curves are compared with those using the ENTEC 2010 methodology [53]. The results shown in Table 6 show the agreement between the values given for the engine operation and the values obtained with ENTEC, so the operating regimes shown in the table will be taken as a basis.

Table 6. Comparison of fuel consumption (*FC*) according to SFC curve and SFC ENTEC_2010 [53].

Engine Type	Trip Phase	Assumptions	*LF* (%)	*FC* (t/h)	*FC* Variation with Respect to ENTEC_2010
Main engine	Hotelling	2 engines	20	0.587	+1.6
		ENTEC_2010	20	0.578	-
	Navigation	2 engines	80	1.879	−10.7
		ENTEC_2010	80	2.105	-
	Manoeuvring	2 engines	20	0.587	+1.6
		ENTEC_2010	20	0.578	-
Auxiliary engine	Hotelling	2 engines	40	0.104	−3.6
		ENTEC_2010	40	0.108	-
	Navigation	2 engines	30	0.084	+4.1
		ENTEC_2010	30	0.081	-
	Manoeuvring	2 engines	50	0.124	−7.7
		ENTEC_2010	50	0.135	-

2.2.3. Navigation Base Scenarios

As mentioned in the previous sections, two types of Base Navigation are established depending on whether auxiliary engines (AE) or shaft generators (SG) are used for the electrical supply during navigation (Table 7).

Table 7. Base Navigation scenarios: Auxiliary Engine (AE) Navigation Base and Shaft Generator (SG) Navigation Base.

Trip Phase	AE Navigation Base	SG Navigation Base
Navigation	2 MEs; 80% LF 2 AEs; 30% LF	2 MEs with SG and LF > 80% 2 AEs off
Manoeuvring	2 MEs; 20% LF 2 AEs; 50% LF	
Hotelling	2 MEs; 20% LF 5% hotelling time 2 AEs; 40% LF	

- AE Navigation Base: using auxiliary engines:
    - Navigation: load factor of 80% for 2 main engines and 30% for 2 auxiliary engines;
    - Manoeuvring: load factor of 20% for 2 main engines and 50% for 2 auxiliary engines;
    - Hotelling: load factor of 20% for 5% of the time for 2 main engines and 40% for 2 auxiliary engines.
- SG Navigation Base: using shaft generators:
    - Navigation: the load factor of the 2 main engines is increased so that the shaft generators can provide electricity supply; the auxiliary engines are, therefore, out of service;
    - Manoeuvring: idem AE Navigation Base;
    - Hotelling: idem AE Navigation Base.

From the defined AE Navigation Base and SG Navigation Base, the possible alternatives to be considered will be aimed at taking the auxiliary engines out of service in the port to reduce emissions. Therefore, it will be essential to know the fuel and emission costs during the ship's stay in port in order to reference the different alternatives to them.

2.3. Incorporating Batteries in the Vessel

The aim of incorporating batteries in the vessel is to use them to supply the ship with electricity during its stay in port.

In this section, first, a reference battery is selected, and its basic parameters for calculation are specified.

Below, the alternatives to the Base Navigation scenario are defined according to whether charging is performed by the auxiliary engines or shaft generators while the vessel is navigating.

2.3.1. Battery Specifications

To size the batteries, those used in [22] are taken as a reference, and we select the ones that best fit our application. As a result, the specifications shown in Table 8 are obtained from the published ones and the manufacturer's information. Special attention is paid to the chosen battery so that the charging and discharging times are compatible with the strategy proposed in this study.

Table 8. Characteristics of Corvus Blue Whale battery.

	Corvus Blue Whale (Pack: 6 Strings) [56]
Chemistry	LFP
Usable energy (kWh)	3726
Nominal voltage (V)	1109
Efficiency (%)	90
Depth of discharge (%)	90
C-rate (discharge/charge)	0.7 C
Time (discharge/charge)	1.4 h
Estimated useful life (years)	10
High (mm)	2755
Width (mm)	1390
Depth (mm)	10,047
Weight (kg)	37,296
Specific energy (Wh/kg)	99.90
Energy density (Wh/m^3)	96.84
Cost (EUR/kWh)	471.7

For calculation purposes, a maximum state of charge of the battery (*SOCmax*) of 90% is considered [21,57,58], which will favour a greater number of battery cycles than with an SOC of 100% [59].

For the subsequent sizing of the battery, an inverter-battery charger with an efficiency of 98.3% is also selected as a reference [60].

2.3.2. Battery Charging Strategies during Navigation

The batteries are charged during navigation by the auxiliary engines or shaft generators, based on the types defined above.

Charging the batteries during navigation offers two advantages:

- It supplies the electrical demand in port, allowing the auxiliary engines to be shut down to avoid their emissions.
- During battery charging, the engines operate at a higher load factor than the auxiliary engines in port. Therefore, as the SFC decreases with the load factor (Figures 2 and 3), the efficiency of the engines will be greater.

When incorporating batteries, the following charging strategies are defined based on the Navigation Base scenarios. All alternatives have the following in common:

- Manoeuvring operations do not vary;
- The auxiliary engines are turned off in port, and the main engines will function according to the Navigation Bases.

Regarding the navigation phase, the following scenarios will be analysed:

- AE_A Charge: The auxiliary engines are used for power supply and battery charging, so their load factor is raised while charging the battery and reduced to 30% the rest of the time (2AE_bat). The two main engines will operate according to AE Navigation.
- SG_A Charge: The batteries are charged by the shaft generators, so the load factor of the main engines is raised while the batteries are being charged and continues the rest of the time according to SG Navigation (2ME_SG_bat). The two auxiliary engines are out of service.
- SG_B Charge: The main engines operation is unchanged compared to the Base Scenario, and the auxiliary engines are only used for battery charging (2AE_SG_bat).

2.4. Onshore Power Supply (OPS)

To analyse the feasibility of the OPS installation in relation to fuel consumption in port, it is essential to know the following:

- The price to be paid for the port's electricity supply;
- The emission factor of electricity generation.

In Table A2 of Appendix A, electricity prices are compiled for different ports in Spain, France, Belgium, the Netherlands, and Morocco for 2023. Of the Spanish ports, only those that specify supply to a ship are selected except in the case of the Port of Vigo, as it is included in the route to be analysed. In most ports, the electricity price is a fixed value in EUR/kWh.

Table A4 shows the emission factors for electricity generation for 2023 in different European countries obtained from the ELECTRICITY MAPS application [61].

2.5. Alternatives Selection Methodology

As already mentioned in the Introduction, the articles consulted and their methodologies focus only on one part of the subject of this article: the operation and charging of batteries with shaft generators [19,20] or auxiliary motors [21,22], the calculation of the consumption and emissions of hybrid systems for container ships [21] or ferries [22], and the OPS costs in port [34] or hybrid systems [58]. None of the methodologies consider the alternatives proposed in this article as a whole and with their calculation of fuel costs and emissions.

Therefore, taking these references as a basis, Figure 4 defines the methodology for selecting the alternative to be applied. This methodology is based on the established method for calculating the consumption and emissions costs and considers the costs of each of the Base Navigation scenarios, the battery charging strategies, and the use of OPS.

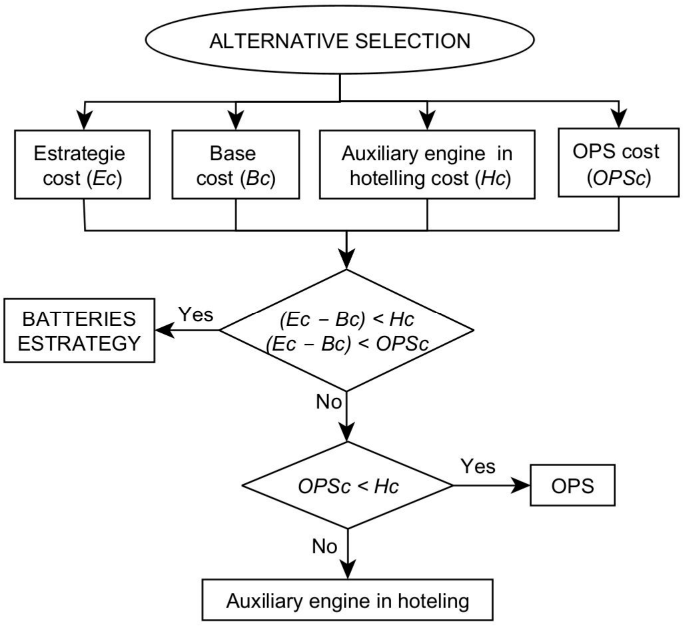

Figure 4. Definition of alternative selection methodology.

Firstly, a charging strategy (AE_A, SG_A, or SG_B) can be chosen as long as the difference between the cost of that charging strategy (*Ec*) and the cost of its corresponding base scenario (*Bc*) is less than the auxiliary engine cost in hotelling (*Hc*) and OPS cost (*OPSc*)

Next, if one of these two conditions is not met, OPS can be chosen if its cost (*OPSc*) is lower than the auxiliary engine in hotelling cost (*Hc*). Otherwise, no alternative can be selected.

This methodology could be applied to both the annual cost of the route and the cost per trip. In this article, it will be used on the annual cost of the route.

3. Application to Ro-Ro Ships in a Maritime Route between Montoir and Vigo Ports

The alternatives analysis will be carried out on a regular maritime route between the Port of Montoir (France) and the Port of Vigo (Spain). Specifically, it will correspond to the route between Montoir and Vigo, with a stay in the port of Vigo (Figure 5), carried out by a Ro-Ro vessel similar to the Suar Vigo (Table A1).

Figure 5. Maritime route Montoir–Vigo.

This route was selected because it is more than 50 years old, was designated Motorway of the Sea in 2015 by the European Union, and has been operated by the Suardiaz shipping company since 2013. [62]. This route does not fall within any ECA area, but it should be noted that it calls in European ports.

Furthermore, the vessel Suar Vigo is taken as a reference because it belongs to the Suardiaz shipping company and is one of the vessels that normally operates this route, according to the tracking of Ro-Ro vessels that stopped in Vigo between July 2021 and March 2022 [63].

Therefore, during navigation, the limit for the sulphur content of used fuels must not exceed 0.5% m/m, in accordance with Annex VI of the MARPOL Convention and Directive (EU) 2016/802. However, when calling in port, this limit must be reduced to 0.1% m/m according to Directive (EU) 2016/802. This restriction means that fuel used in port will be more expensive than fuel used at sea.

According to the tracking of Ro-Ro vessels stopping in Vigo [63], an average sailing time between Montoir and Vigo of 32.80 h can also be estimated. According to the SEA-DISTANCES.ORG website [64], the distance between the two ports is 464 nm, and an average speed of 15 knots (27.78 km/h) could be considered on the basis of the records for the vessel provided by the vesseltracker.com website [65]. Therefore, the cruising time would be 30.93 h, close to the time obtained from the tracking.

The average time spent in port will be considered to be 20 h [63], and for manoeuvring, 1 h [44].

The number of voyages and berths corresponds to the 79 annual berths made by the Suar Vigo in 2018 [63,66].

3.1. Calculation of Navigation Bases Costs

According to the two basic navigation types defined in Section 2.2.3, the annual cost (fuel and emissions) is calculated considering the SFC curve obtained for each of the engine types (main and auxiliary).

If the electrical demand of the ship is to be met during navigation with the auxiliary engines, AE Navigation Base, the power supplied by the main engines during the navigation phase, with a load factor of 80%, is considered to be exclusively for navigation.

On the other hand, if the demand is covered by the shaft generators, SG Navigation Base, the load factor of the main engines will have to be raised to 83%, according to Table 9.

Table 9. Percentage load factor (*LF*) of main engines (MEs) during navigation using auxiliary engines (AE Navigation Base) or shaft generator (SG Navigation Base) for power supply.

	AE Navigation Base	SG Navigation Base
Main engine nominal power, P_{n_ME} ($\mathrm{kW_m}$)	12,960	
Main engine load factor, LF_{ME} (%)	80	83
Power load factor, P_{LF_ME} ($\mathrm{kW_m}$)	10,368.00	10,732.21
Navigation power, P_{nav_ME} ($\mathrm{kW_m}$)	10,368.00	
Shaft generator load factor, LF_{SG} (%)	0	27
Auxiliary engine nominal power, P_{n_AE} ($\mathrm{kW_m}$)	1240	
Auxiliary engine load factor, LF_{AE} (%)	30	0
Electrical power supply ($\mathrm{kW_m}$)	372	364.21
Electrical power supply ($\mathrm{kW_e}$)	347.82	

In both Navigation Bases, 0.5% VLSFO fuel will be used during the navigation and manoeuvring phases, and 0.1% MGO will be used while the vessel is berthed in port.

Tables 10 and 11 show the costs for the main and auxiliary engines for each of the Navigation Bases and trip phases. The costs for the manoeuvring and hotelling phases are the same for both bases. However, the navigation phase is different, depending on whether auxiliary engines or shaft generators are used to meet the ship's electrical power demand.

Table 10. Costs according to Navigation Bases and trip phases of main engines.

	AE Navigation	SG Navigation	Manoeuvring	Hotelling
Fuel consumption (t/route)	61.64	63.55	0.59	0.59
Fuel cost (EUR/route)	39,021.24	40,228.14	371.83	523.11
CO_2 emissions (t/route)	195.96	202.02	1.87	1.87
CO_2 emissions cost (EUR/route)	15,618.28	16,101.34	148.83	148.83
Trip cost (EUR/route)	54,639.52	56 329.48	520.66	671.94
Annual cost (EUR/year)	4,316,522.21	4,450,028.84	41,131.77	53,082.97

Table 11. Costs according to Navigation Bases and trip phases of auxiliary engines.

	AE Navigation	SG Navigation	Manoeuvring	Hotelling
Fuel consumption (t/route)	2.76	N/A	0.12	2.08
Fuel cost (EUR/route)	1745.02	N/A	78.59	1848.86
CO_2 emissions (t/route)	8.76	N/A	0.39	6.60
CO_2 emissions cost (EUR/route)	698.45	N/A	31.46	526.00
Trip cost (EUR/route)	2443.47	N/A	110.05	2374.86
Annual cost (EUR/year)	193,033.74	N/A	8693.84	187,614.00

Since the possible alternatives to the Navigation Bases aim to avoid the use of auxiliary engines in port, their savings will be calculated on the basis of the annual cost of the auxiliary engines in port (fuel and emissions). This cost amounts to EUR 187,614 and represents 78% of the annual cost of the engines in berth (main and auxiliary), according to Figure 6. It should be noted that port consumption is assumed to be 5% of the annual cost of the route, including navigation, manoeuvring, and hotelling.

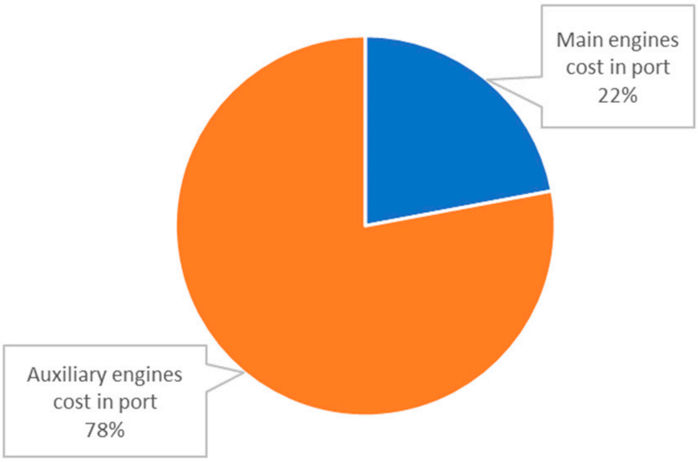

Figure 6. Percentage costs of main and auxiliary engine's with respect to the annual cost in port.

Finally, Figure 7 shows the time evolution of the LF in the different phases of the journey for both Navigation Bases.

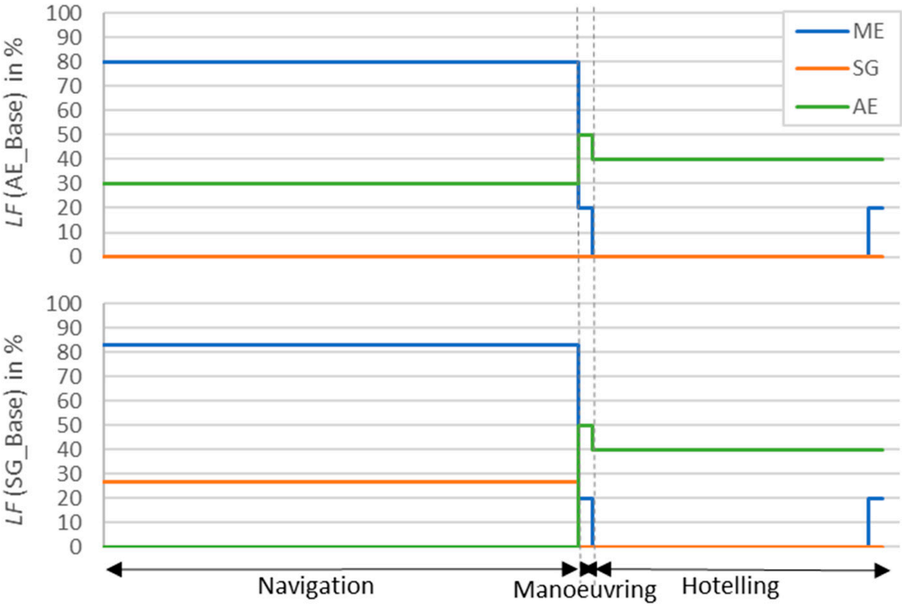

Figure 7. Comparison of the time evolution of the load factor (*LF*) between Navigation Bases (AE and SG) for each of the voyage phases.

3.2. Integration of Batteries in the Vessel

When using the battery selected as the reference in Section 2.3.1, first, the capacity needed to meet the electricity needs in port is calculated. Subsequently, the costs for each of the navigation alternatives defined in Section 2.3.2 are obtained in order to compare them with the cost of using auxiliary motors in port and obtain their possible savings.

3.2.1. Battery Sizing

Taking into account the characteristics of the battery selected (Table 8) and a round-trip efficiency of 90% [67,68], the battery capacity required to supply the electricity demand in port is 14,902 kWh (Table 12). With this capacity, the battery will take 22.22 h to reach the minimum battery capacity (C_{batmin}), which is longer than the hotelling time. Therefore, the battery has sufficient capacity to meet the demand in port.

Table 12. Corvus Blue Whale battery sizing for in-port supply.

Battery Data	
Model	Corvus Blue Whale
Capacity per battery (kWh)	14,902
Round-trip efficiency (%)	90
$SOC_{máx}$ recommended (%)	90
SOC_{min} recommended (%)	10
Battery pack	
Number of battery packs	4
Battery capacity per pack (kWh)	3726
Hotelling discharge time, t_d (h)	22.22
Volume (m^3)	153.90
Weight (t)	148.19
Weight/GT (%)	0.9
Weight/DWT (%)	3.4
Cost (EUR/kWh)	471.7
Cost (EUR)	7,029,057

Moreover, the total weight of the batteries accounts for only 0.9% of the gross tonnage (GT) and 3.4% of the deadweight (DWT) of a vessel like the Suar Vigo. Consequently, as such low percentages are obtained, it is not considered to affect the seaworthiness of the ship nor is consumption considered to increase significantly.

Finally, an investment in batteries is estimated at around EUR 7 million, at a rate of around 472 EUR/kWh. In addition, apart from the fuel savings in port, the feasibility of the batteries should also consider the following:

- That a significant reduction in battery prices is expected by 2030 [11,12];
- The evolution of fuel prices, electricity prices, emissions, taxes, etc.

3.2.2. Costs of Charging Strategies during the Navigation Phase

Based on the criteria set out in Section 2.3.2 for charging strategies, their annual costs are calculated. These strategies are intended to ensure that in port, the auxiliary engines remain off, and the main engines will operate in accordance with the Navigation Bases (the two main engines at a 20% load factor for 5% of the time in port).

The manoeuvring operations, however, do not vary compared to the Navigation Bases (two main engines at 20% load factor and two auxiliary engines at 50%). Therefore, only the navigation phases need to be calculated for each of the alternatives, depending on whether auxiliary engines or shaft generators are used to charge the batteries.

AE_A Charge Strategy

In this charging strategy, the auxiliary engines are used for the ship's power supply and battery charging. Therefore, the load factor of auxiliary engines is raised during the charge time, and the rest of the time it is reduced to 30% (2AE_bat).

The main engines will work according to the AE Navigation Base (80% load factor).

According to the SFC curve for the auxiliary engines, the lowest consumption occurs at 100% charge, although from 80%, it stabilises considerably (Figure 3).

However, to select the load factor at which the auxiliary engines will operate, their evolution will first be analysed together with the charge time and navigation time. In Figure 8, the charge time must be less than the estimated navigation time (32.80 h). Therefore, the load factor of auxiliary engines will have to be greater than or equal to 58%.

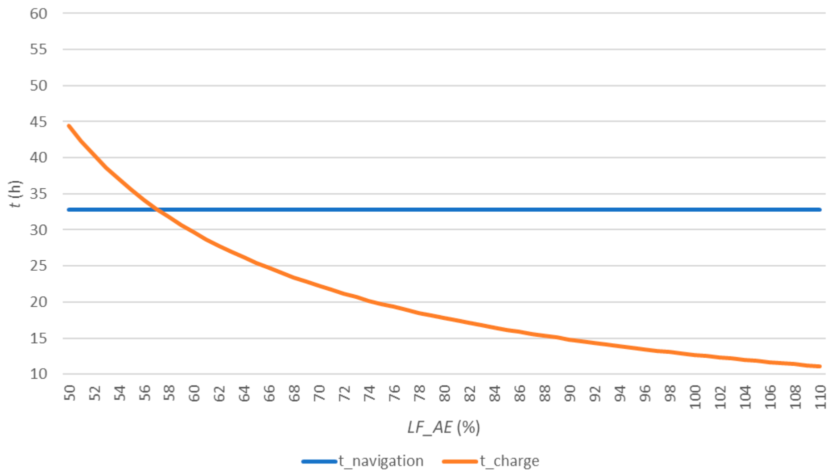

Figure 8. Battery charging time (t_{charge}) and navigation time ($t_{navigation}$) according to the load factor of the ship's auxiliary engines, AE_A Charge.

On the other hand, Figure 9 shows that the cost of the total fuel consumption (*FC*) per route increases slightly with the load factor. In fact, from a 58% to 100% load factor, the increase would only be 2.4%. This total cost is calculated as the sum of the cost while the batteries are being charged; for the rest of the time, the following occurs:

- The cost during battery charging decreases as the load factor increases, as does the SFC, according to Figure 3.
- The cost of fuel consumption for the rest of the time increases because as the battery charging time decreases (Figure 8), the time during which the auxiliary motors run at 30% (lower efficiency) increases.

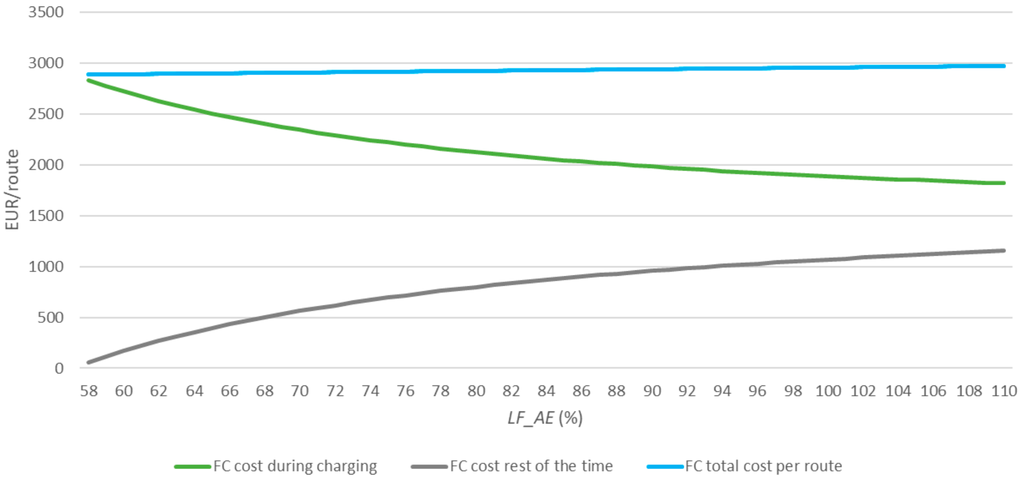

Figure 9. Fuel consumption (*FC*) cost during charging, fuel consumption cost rest of time at 30% load factor, and fuel consumption total cost per route according to the load factor of the ship's auxiliary engines, AE_A Charge.

As shown in Figure 9, the lowest fuel cost per route occurs with 58% of the load factor of the auxiliary engines and corresponds to a charge time of 31.75 h. However, as this time is very close to the average navigation time (32.8 h), the charge time is proposed to be reduced by around 10% in case of possible unforeseen navigation events. Consequently, the selected charge time will be 28.67 h for a load factor of auxiliary engines of 61% (Table 13), and the annual cost would increase by only 0.17%.

Table 13. Analysis of the performance of auxiliary engines for the AE_A Charge strategy.

	AE_A Charge **2AE_bat**
Nominal power, P_n (kW_m)	1240
Load factor during charge, LF_{bat} (%)	66
Load factor rest of time, LF_{rest} (%)	30
Power to battery load factor, P_{LFbat} (kW_m)	707.23
Electrical power supplied, P_e (kW_e)	347.82
Battery electrical power, P_{bat} (kW_e)	359.41
Battery charging time (h)	28.67
Fuel consumption (t/route)	4.57
Fuel cost (EUR/route)	2891.85
CO_2 emissions (t/route)	14.52
CO_2 emissions cost (EUR/route)	1157.47
Trip cost (EUR/route)	4049.32
Annual cost (EUR/year)	319,896.42

SG_A Charge Strategy

If the aim is to charge the batteries during navigation with the shaft generator, the charge percentage of the main engines would have to be increased. During navigation, the auxiliary engines remain switched off.

According to Figure 2, the lowest *SFC* would occur with the load factor of main the engines at 100%. However, the load factor of the shaft generator must also be considered.

According to the SG Navigation Base, the shaft generators supply the ship's electrical needs with a load factor of 27% and for the main engines with 83%. Therefore, the increased power obtained by raising the corresponding load factors can be used to charge the battery (under normal sailing conditions).

Figure 10 shows that the charge time is shorter than the navigation time (32.80 h) at a load factor of 85.4%.

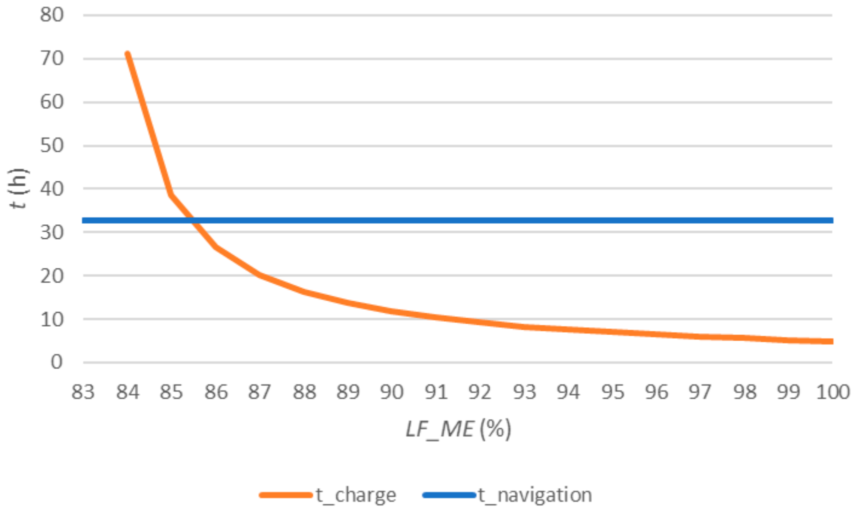

Figure 10. Battery charging time (t_{charge}) and navigation time ($t_{navigation}$) according to the load factor of the ship's main engines, SG_A Charge.

To calculate the load factor at which the main engines must work, the following must be considered:

- The power distribution and load factor for navigation and power supply, as given in Table 9;
- The shaft generator must not exceed 100% of the load factor for proper operation.

The mechanical power of the shaft generator working at 100% is 1358 kW_m. Therefore, if the main engine is to approach but not exceed this power, it will have to raise its load factor from 80% (navigation power) to 90.47% (Table 14). The rest of the time, it will be reduced to 27% and 83%, respectively (2ME_SG_bat).

Table 14. Percentage load factor (*LF*) of the main engines (ME) and shaft generators (SG) for power supply and battery charging.

	SG Navigation Base	**SG_A Charge**
Main engine nominal power, P_{n_ME} (kW_m)	12,960	
Main engine load factor, LF_{ME} (%)	83	90.47
Power to load factor, P_{LF_ME} (kW_m)	10,732.21	11,724.91
Navigation power to 80% of main engines' load factor, P_{nav_ME}	10,368.00	
Shaft generator load factor, LF_{SG} (%)	27	100
Mechanical power supplied by shaft generator during charge, P_{SG} (kW_m)	364.21	1356.91
Battery mechanical power with SG, P_{bat} (kW_m)	0	992.70
Battery electrical power with SG, P_{bat} (kW_e)	0	948.03
Electrical power supply (kW_m)	364.21	
Electrical power supply (kW_e)	347.82	

Table 15 shows the results of the analysis for the SG_A Charge strategy. Charging the battery during navigation will take 10.87 h, less than the estimated navigation time.

Table 15. Analysis of the operation of the main engines and shaft generators for battery charging in SG_A Charge.

	SG_A Charge 2ME_SG_bat
Main engines' nominal power, P_n (kW_m)	12,960
Main engines' load factor during charge, LF_{ME_bat} (%)	90.47
Main engines' load factor rest of time, LF_{ME_rest} (%)	83
Shaft generators' load factor during charge, LF_{ME_bat} (%)	100
Shaft generators' load factor rest of time, LF_{ME_rest} (%)	27
Electrical power supplied by shaft generator during charge, P_{SG} (kW_e)	1295.85
Battery electrical power with SG, P_{bat} (kW_e)	948.03
Battery charging time (h)	10.87
Fuel consumption (t/route)	65.28
Fuel cost (EUR/route)	41,324.95
CO_2 emissions (t/route)	207.53
CO_2 emissions cost (EUR/route)	16,540.34
Trip cost (EUR/route)	57,865.30
Annual cost (EUR/year)	4,571,358.42

SG_B Charge Strategy

In this strategy, the shaft generators supply power to the ship, but the batteries are charged by the auxiliary engines. Therefore, the power obtained from the auxiliary engines is devoted to charging the batteries, which will be switched off at the end of the charging process.

In Figure 11, it can be appreciated that the fuel cost per route and charge time decreases as the load factor of the auxiliary engines increases. The lowest cost is obtained for a load factor of 98%, with a charge time of 9.07 h (Table 16).

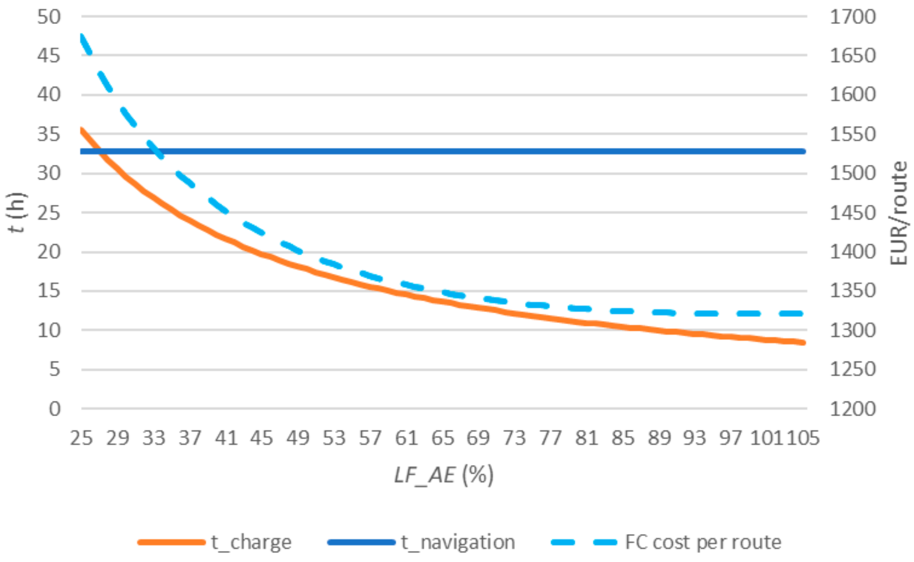

Figure 11. Battery charging time (t_{charge}), navigation time ($t_{navigation}$), and fuel consumption (*FC*) cost per route according to the load factor of the ship's auxiliary engines, SG_B Charge.

Table 16. Performance analysis of auxiliary engines for battery charging in SG_B Charge.

	SG_B Charge 2AE_SG_bat
Nominal power, P_n (kW_m)	1240
Load factor during charge, LF_{bat} (%)	98
Load factor rest of time, LF_{rest} (%)	0
Power to battery load factor, P_{LFbat} (kW_m)	1240
Battery electrical power, P_{bat} (kW_e)	1136.21
Battery charging time (h)	9.07
Fuel consumption (t/route)	2.09
Fuel cost (EUR/route)	1321.22
CO_2 emissions (t/route)	6.64
CO_2 emissions cost (EUR/route)	528.82
Trip cost (EUR/route)	1850.04
Annual cost (EUR/year)	146,153.02

Figure 12 below shows the time evolution of the *LF* for each of the charge strategies in the different phases of the journey.

Calculation of the Savings Obtained with the Sailing Alternatives with Respect to the Fuel Consumption and Emissions of Auxiliary Engines in Port

The total costs for each of the phases (navigation, manoeuvring, and hotelling) are calculated from the operation of the engines in each of the alternatives (Section 2.3.2).

Taking into account the methodology for the selection of alternatives set out in Figure 4, it can be seen that the difference in the cost of each of the strategies compared to their baseline scenario is less than the cost of consumption of the auxiliary engines in port.

As Figure 13 shows, in all strategies, there are savings with respect to the use of fuel in port, regardless of whether the batteries are charged with auxiliary engines or shaft generators. The greatest savings (35.3%) are obtained when the shaft generators are used to meet the electricity supply for the vessel and charge the batteries during navigation.

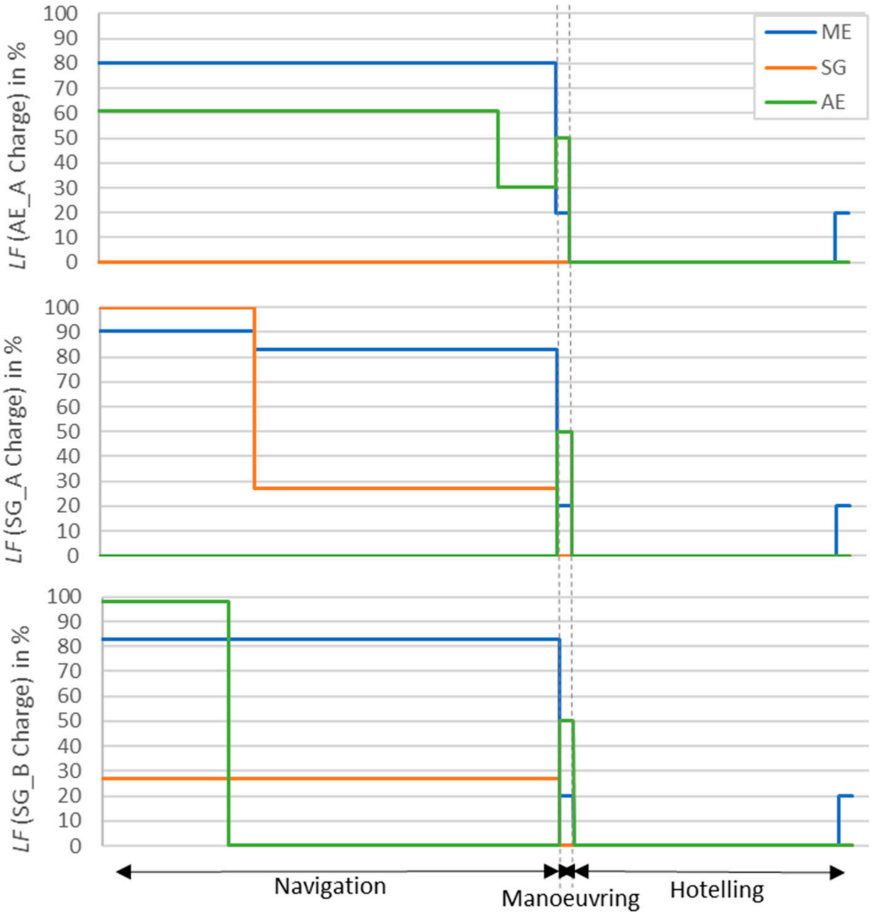

Figure 12. Comparison of the time evolution of the load factor (*LF*) for the different charge strategies (AE_A, SG_A, and SG_B) in each stage of the journey.

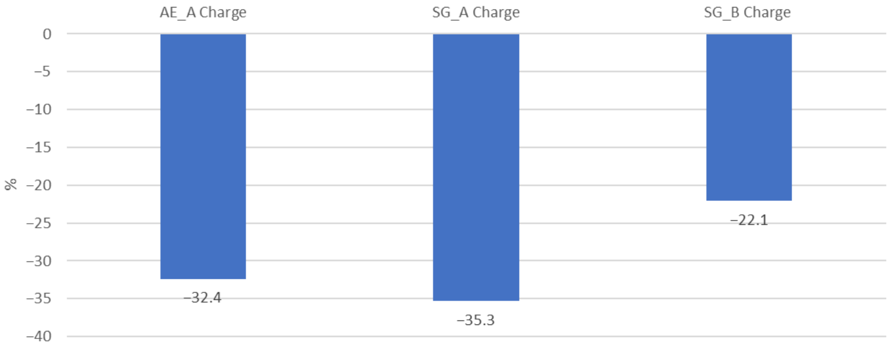

Figure 13. Cost variation of loading strategies versus use of auxiliary engines in port (%).

On the other hand, the variation in the annual emissions of the proposed alternatives compared to those produced in port by the auxiliary engines is also analysed.

If the auxiliary engines in port are turned off and the batteries are used instead, their emissions are zero. That is, the reduction in emissions is 100%. However, in the navigation phase, variations in emissions are produced to supply electricity to the ship and charge the batteries. Therefore, emissions along the entire route must be considered as well and not only while the ship is in port.

The percentage of variation in emissions is calculated following the same procedure used for the variation in costs. Thus, taking into account the difference in emissions of each of the strategies compared to their baseline scenario and the emissions of the auxiliary engines in port, the percentages of reduction or increase in emissions are obtained (Figure 14). Although the three alternatives produce savings in the total annual costs (fuel and emissions), only two loading strategies achieve savings with respect to the annual emissions of the ship: SG_A Charge (16.5%) and AE_A Charge (12.7%). However, the third strategy (SG_B Charge) only shows an increase in emissions of 0.5%.

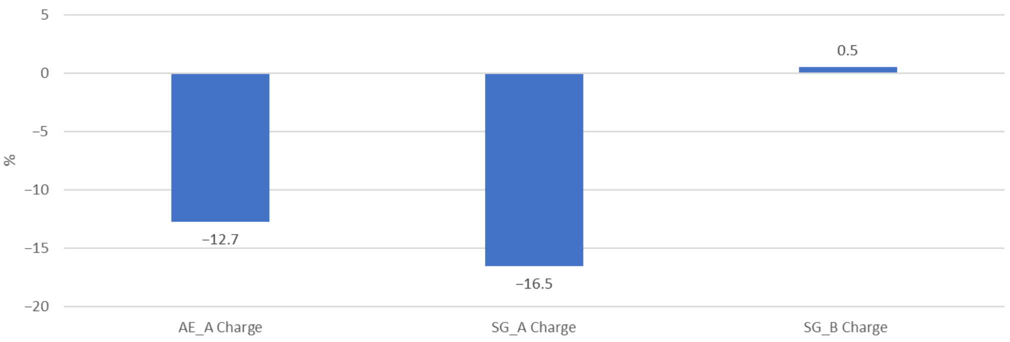

Figure 14. Emission variation of loading strategies versus use of auxiliary engines in port (%).

3.2.3. Onshore Power Supply Costs

Another way to reduce the emissions from auxiliary engines in port, in order to shut them down, would be through onshore power supply (OPS).

As the route considers the stay in the Port of Vigo, this analysis will take into account what is specified in Section 2.4 and the electricity prices of the Spanish ports reflected in Table A2.

In addition, the emission factor for electricity generation in Spain for the year 2023 should be taken into account, which is 0.12989 t CO_2 eq/MWh (Table A4).

The annual emissions and electricity costs for the Spanish ports considered are calculated below (Table 17).

Table 17. Annual electricity costs and emissions from port demand using OPS.

	OPS_Vigo	OPS_Tenerife	OPS_Sevilla	OPS_Baleares	OPS_Melilla
Docking electrical demand (kWh/docking)	9275.20				
Annual electrical demand (kWh/year)	732,740.80				
Electricity emission factor 2023 (t CO_2 eq./MWh)	0.12989				
Price (EUR/kWh)	0.3195	0.2344	0.6666	0.0359	Variable
Docking electricity cost (EUR/docking)	2963.43	2174.11	6182.85	332.52	-
Annual electricity cost (EUR/year)	234,110.69	171,754.44	488,445.02	26,268.76	220,518.81
Docking electricity emissions (t/docking)	1.20				
Annual electricity emissions (t/year)	95.18				
Docking electricity cost emissions (EUR/docking)	96.02				
Annual electricity cost emissions (EUR/year)	7585.50				
Annual cost (EUR/year)	241,696,19	179,339.95	496,030.52	33,854,26	228,104.31

In accordance with the selection methodology for alternatives set out in Figure 4, the annual costs obtained for the different OPS scenarios are compared with the hotelling costs with auxiliary engines calculated in Table 11. Only in the Ports of Islas Baleares and Santa Cruz de Tenerife are the costs lower with OPS; in all other scenarios, they increase.

According to Figure 15, this results in annual cost savings of the following:

- 82% in the case of OPS in the Baleares Ports, mainly due to the 90% subsidy on electricity prices;
- 4.4% in the case of the Port Authority of Santa Cruz de Tenerife.

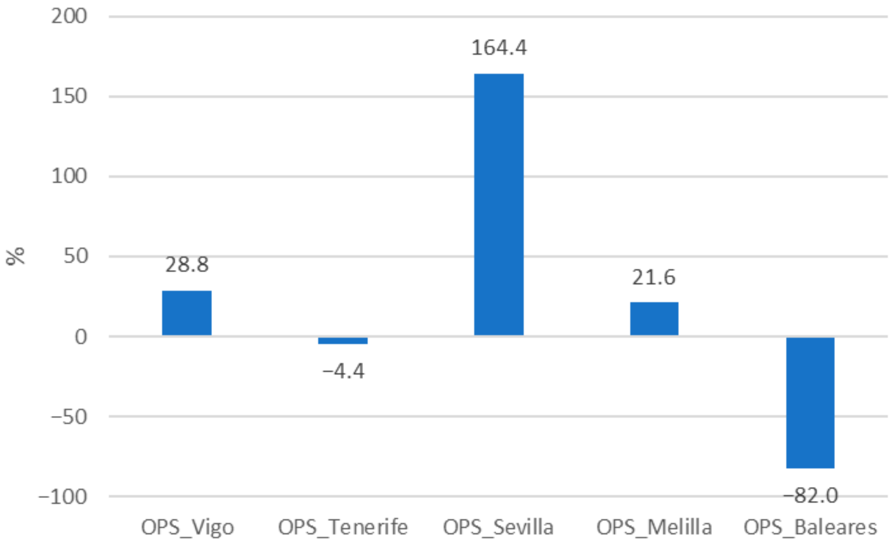

Figure 15. Cost variation of OPS scenarios as opposed to use of auxiliary engines in port (%).

Moreover, it can be seen that the difference in prices between ports and their possible subsidies will have an important influence on the viability of the system for supplying electricity to the ship from the port.

Finally, by using OPS instead of auxiliary engines in the different ports, emission savings of 81.7% are obtained. The savings are the same in all ports because they are Spanish, and the same emission factor for electricity generation is used for their calculation.

4. Comparison of Results and Discussion

Taking into account the selection methodology for alternatives established in Figure 4, it is found that, for the Montoir–Vigo route, the difference in the cost of each of the strategies with respect to the Base Scenario is lower than the consumption cost of using auxiliary engines in port and the use of OPS in the Port of Vigo. Therefore, the use of batteries would be a better option than the use of OPS.

Figure 16 takes all the proposed alternatives for incorporating batteries and onshore power supply (OPS) and compares them with the use of auxiliary engines in port. For the selected route, the three charging strategies produce savings between 22.1 and 35.3%. The best option would be to use the shaft generators to supply power and charge the batteries (Charge SG_A), with savings of 35.3%. However, if the shaft generators could not be used, supplying power and charging the batteries with the auxiliary engines (Charge AE_A) would also produce savings of 32.4%.

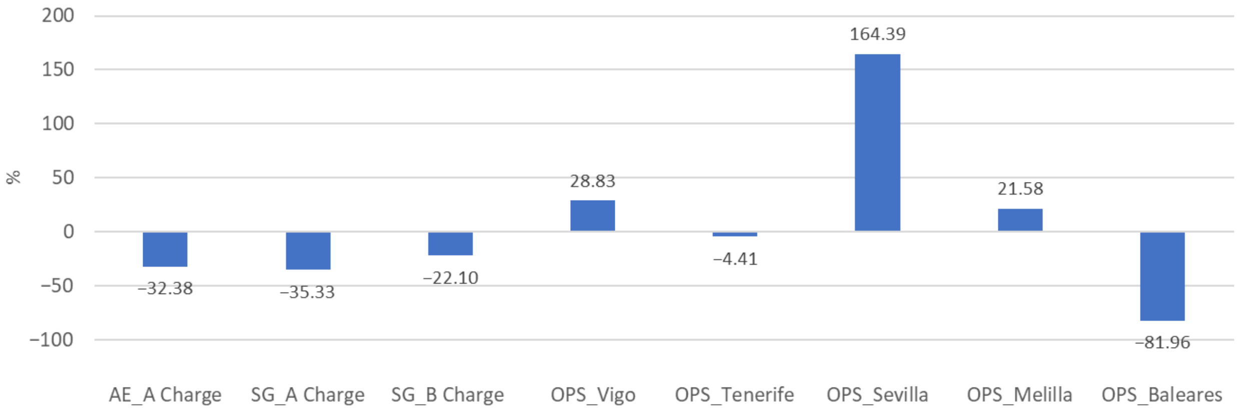

Figure 16. Cost variation of proposed alternatives versus use of auxiliary engines in port (%).

With regard to the OPS alternatives evaluated for the different Spanish ports, the most advantageous would be that of the Port Authority of Islas Baleares, with savings of 82%, as the price of electricity there has a 90% subsidy. This analysis shows that the use of OPS is highly conditioned by the great variation in prices between the different ports and the existence of possible subsidies.

Table 18 shows that once the electricity price falls below 0.24570 EUR/kWh, savings are obtained by using OPS, and the prices at which savings are equivalent to those obtained with battery strategies could be achieved.

Table 18. Electricity prices according to savings percentages.

Saving (%)	Electricity Price (EUR/kWh)
0	0.24569
22.10	0.18910
32.38	0.16728
35.33	0.15523

Regarding the emissions analysis from the different alternatives, the obtained reduction with the use of OPS (81.7%) is much more significant than with the alternatives with batteries. Of the three alternatives, only two loading strategies achieve savings with respect to the annual emissions of the ship: SG_A Charge (16.5%) and AE_A Charge (12.7%). However, the third strategy (SG_B Charge) only shows an increase in emissions of 0.5% (Figure 17).

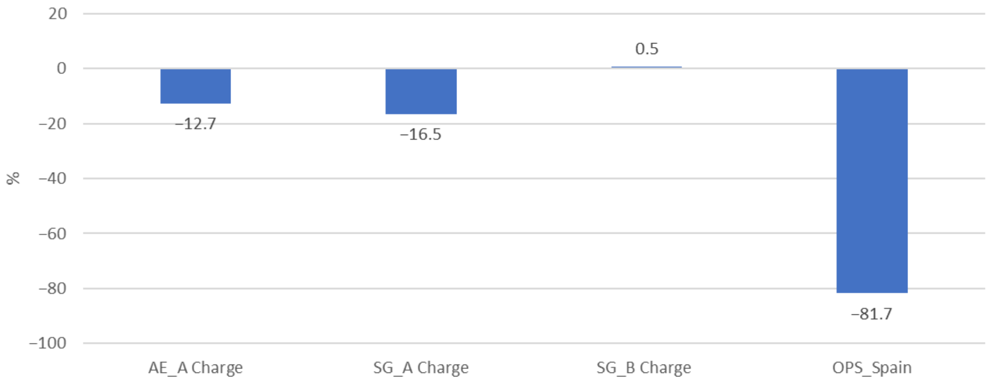

Figure 17. Emission variation of proposed alternatives versus use of auxiliary engines in port (%).

5. Conclusions

This article has established a methodology for choosing between two alternatives for emission reductions in port (Figure 4) when shutting down the auxiliary engines: the incorporation of batteries in the ship and onshore power supply (OPS).

This methodology is applied on a regular maritime route between the European ports of Montoir (France) and Vigo (Spain), carried out by a Ro-Ro-type vessel similar to the Suar Vigo.

With batteries incorporated, the charging strategies were to charge them during navigation with either the auxiliary engines or the shaft generators. Therefore, in addition to reducing port emissions, the efficiency of the engines is also improved. While charging the batteries, the engines operate at higher load factors than when the ship is in port. Furthermore, due to limitations on the sulphur content of fuels that must be complied with in European ports, these fuels are often more expensive than those used during navigation.

From the point of view of reducing the annual costs (fuel consumption and emissions) of the ship, the analysis shows that the best alternative for the Montoir–Vigo route is the incorporation of batteries on board the ship, with annual cost savings of between 22 and

35% depending on the strategy. The best option is for the shaft generator to provide the electrical power and charge the battery, with savings of 35%. The viability of the OPS system will mainly depend on the variation in electricity prices between ports and on the possible subsidies applied by each port. The cost structure is very heterogeneous. In fact, in the Port of Vigo costs would increase by 29% by using the OPS system, while if the ship docked in the Ports of the Balearic Islands, it would obtain savings of 82%, since there, the price of electricity has a 90% subsidy.

From the point of view of the reduction in annual emissions of the ship, although the reduction in emissions in port is 100% with the use of batteries, variations in emissions during navigation are produced to supply electricity to the ship and charge the batteries. Therefore, emissions along the entire route must be considered as well and not only while the ship is in port. Consequently, the best option is the incorporation of the OPS system, with savings of 81.7%. Of the three alternatives with the incorporation of batteries, only two obtain emission savings when considering the entire route: the SG_A Charge strategy of 16.5% and AE_A Charge of 12.7%.

Finally, the defined methodology can be extrapolated to other ports, routes, and types of vessels, complementing it with real data on the operation of the vessels.

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Appendix A. Information about Suar Vigo Ship and OPS

First, the main characteristics of the selected vessel, the Suar Vigo, are detailed.

Table A1. Main characteristics of the Suar Vigo ship [51,63,66].

	Suar Vigo
Gross tonnage, GT	16,361
Dead weight, DWT	4400
Annual berths	79
Hours per year	1601
Average time spent berthing (h)	20
Number main engines	2
Main engine power (kW_m/each one)	6480
Number of shaft generators	2
Shaft generator power (kW_m/each one)	679
Shaft generator efficiency (%)	0.955
Number of auxiliary engines	2
Auxiliary engine power (kW_m/each one)	620
Auxiliary engine efficiency (%)	0.935

In accordance with Section 2.4, this appendix includes the information needed to calculate the OPS alternatives: electricity prices in different European ports, prices of a tariff in Spain with six time bands and a voltage level above 1 kV and below 30 kV, and electricity generation emission factors for different European countries.

As can be seen in Table A2, the price of electricity in most ports is a fixed value, although there are some exceptions or particularities:

- In the Port of Marseille (France), the price is different for the summer season (April to September) and winter (October to March).
- In the Port of Melilla (Spain), the price is broken down into a variable term (T_v) for consumption, as billed by the supplier, and a fixed term (T_f) corresponding to the use of the networks and supply installation. Regarding the variable term, the most appropriate tariff for OPS supply in Spain would be a six-band tariff for payment for energy and power, with a voltage level above 1 kV and below 30 kV [69]. The energy price per band is shown in Table A3.
- In the Port of Islas Baleares, there is a fixed price for electricity, although with a 90% rebate if it is OPS. This, therefore, makes it the lowest price to be applied in all the ports analysed.

Table A2. Electricity prices in ports.

Country	Port	Concept	Electricity Prices (EUR/kWh)	
Spain	Baleares	Supply to ships and boats 90% discount OPS price	0.3585	[70]
	Melilla	Variable term for consumption	Supplier	[71]
		Fixed term: use of supply grid and facilities		
		- Large-scale consumers (Quarterly consumption > 120,000 kWh/quarter)	0.0692	
		- Others	0.1778	
	Sevilla	Electricity supply to installations, machinery and premises, ships and sporting vessels, or the tourist sector	0.6666	[72]
	Santa Cruz de Tenerife	To ships, platforms, floating structures, etc., from quayside	0.2344	[73]
	Vigo	Low-voltage electricity supply (previous kWh for power)	0.3195	[74]

Table A2. *Cont.*

Country	Port	Concept	Electricity Prices (EUR/kWh)	
France	Metropole Nantes (Montoir)	Electricity supply	0.26	[75]
	Dunkerque	HV electricity supply	0.35	[76]
	Marseille	LV vessel supply	0.3006	[77]
		HV vessel supply winter	0.3107	
		HV vessel supply summer	0.2652	
The Netherlands	Rotterdam Port	Shore power	0.35	[78]
	Harlingen Port		0.484	
	Kampen		0.31	
	Province Zuid-Holland		0.35	
	Zaanstad Inland shipping		0.32	
	Zaanstad River Cruises		0.65	
	Other ports		0.2745	
Belgium	Antwerp Port		0.27	
	De Vlaamse waterweg		0.27	
	North Sea Port		0.2745	
Morocco	Tanger Med	MV electricity supply	0.1373	[79]
		LV electricity supply	0.1623	

Table A3. Electricity price tariff in Spain for six bands with a voltage level greater than 1 kV and less than 30 kV [80].

Band	Energy (EUR/kWh)
1	0.355
2	0.337
3	0.258
4	0.235
5	0.196
6	0.185

Table A4. Emission factors from electricity [61].

Country	Carbon Intensity gCO_2 eq/kWh (Direct)
Spain	129.89
France	39.66
Belgium	126.32
The Netherlands	226.46

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